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Hierarchical Bayesian modeling for predicting ordinal responses of personalized thermal sensation: Application to outdoor thermal sensation data

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ABSTRACT

A concept known as 'nudge' has recently received attention in many application domains. It implies influencing the behavior and decision-making of individuals by making indirect suggestions through the presentation of adequate information. We apply such a perspective to improve the value of a space. It can be measured by the number of visitors, and the predicted thermal sensation is considered as information offered to potential visitors. In the present study, we explain how to generate the information required for a successful nudge. This information must be specifically tailored towards personalized characteristics, rather than a one-fits-all approach. This study presents a new data-driven method for predicting individuals' thermal sensation by formulating the effect of both measured (thermal) and non-measured factors on thermal sensation votes. The proposed model is explicitly encoded based on a major premise that "different individuals have different thermal sensation characteristics; however, all individuals also have a common trend." The inference model uses a Bayesian approach, and is hierarchically structured to represent dependencies across model parameters of the personalized characteristics of individual-level and the typical trend of group-level thermal sensations. The Markov chain Monte Carlo approach is used to approximate the posterior distribution and draw inferences on the model parameters. The results, based on data collected from outdoor spaces, show that the proposed model provides accurate predictions for personalized thermal sensation and improves the efficiency of parameter estimates. Our approach provides fresh insight into statistical models for predicting thermal sensation.

1. Introduction

The thermal environment is an important factor that determines occupant satisfaction, which is not confined only to an indoor space. Due to the need for outdoor activities, which are known for improving the quality of urban life [1,2], people are exposed to the weather. Therefore, an appropriate thermal condition is also important for the enjoyment of outdoor public spaces such as streets, parks, and squares [3–6]. That is, exposure to conditions that are more comfortable can lead to an increase in the number of people who enjoy outdoor spaces [3,7–11]. In fact, evidence exists that the number of visitors in an outdoor space is influenced by the thermal environment in parks/squares [3,7,9], in semi-outdoor spaces [8], and on pedestrian streets [12]. The value of a space can be measured based on the number of visitors [13], and serious efforts are applied to improve this value. However, it is difficult to achieve widely acceptable satisfaction of a thermal environment because individual preferences for thermal conditions vary [14]. Further, it is almost impossible to control outdoor thermal conditions. It would be a simpler task to suggest locations with the preferred thermal environment for a given individual than to offer a space with thermally satisfying responses. We expect that such suggestions will lead to an increase in the number of visitors, and therefore in the value of the space.

This framework of altering people's behavior in a predictable way

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Nomenclature

Symbols

a	shape parameter of the gamma distribution
b	rate parameter of the gamma distribution
BVN	bivariate normal probability density function
D	deviance
G	gamma probability density function
$\mathbf{I}$	identity matrix
IW	inverse Wishart probability density function
L	maximum likelihood
l	lower limit of the uniform distribution
m_0	mean of β_k (k = 0,1,4)
mode of β_k (k = 2,3)	
N	normal probability density function
p	probability
s_k	standard deviation of β_k
U	uniform probability density function
u	upper limit of the uniform distribution
v	underlying metric variable for thermal sensation thermal condition
y	predicted thermal sensation vote
$\mathbf{Z}$	response probability vector
z_r	probability of TSV being r (r = 1, ...7)

Greek letters

α_0	intercept of simple linear regression model
α_1	slope of simple linear regression model
$\boldsymbol{\beta}$	model parameter vector that consists of β_k (k = 0,1,2,3,4)
$\hat{\boldsymbol{\beta}}$	estimates of $\boldsymbol{\beta}$
β_k	model parameter of the proposed model (k = 0,1,2,3,4)
Γ	gamma function
$\boldsymbol{\eta}$	mean vector of β_0 and β_1
$\boldsymbol{\theta}$	threshold vector
θ_j	thresholds (j = 1, ...,6)
$\boldsymbol{\kappa}$	mean vector of the bivariate normal probability density function
$\boldsymbol{\lambda}$	covariance matrix of the bivariate normal probability density function
μ	mean of underlying variable v
ν	degrees of freedom of the inverse Wishart probability density function
$\boldsymbol{\zeta}$	scale matrix of the inverse Wishart probability density function
ρ	the Pearson coefficient
σ	standard deviation of underlying variable v
Φ	normal cumulative distribution function
$\boldsymbol{\psi}$	model parameter vector that consists of β_k (k = 0,1)
$\boldsymbol{\omega}$	covariance matrix of β_0 and β_1

Subscripts

i	number of subjects
n	number of observation data

without economic incentives is known in behavioral science as a "nudge" [15]. The concept of nudging has recently received attention in many application domains, and has proven to be effective in the field of building science [16,17]. According to this concept, individuals' behavior and decision-making are influenced by indirect suggestions through the presentation of adequate information. We believe that if the thermal sensation can be predicted with high accuracy and provided to potential visitors, the number of visitors may increase accordingly. However, the problem lies in accurately predicting the thermal sensation of individuals. Several field studies have shown that this difficulty is attributed to the different thermal sensation characteristics of each individual [18,19]. The success of this nudge hinges on people's understanding of the information given to them [16]. Furthermore, the information must have sufficient value to individuals in relation to their behavior, such that they will decide whether to alter their behavior by, for example, visiting a given space. Therefore, presenting only typical (widely acceptable) trends is insufficient to achieve a successful nudge because it may be less meaningful to some individuals. As such, techniques for learning personalized thermal sensation characteristics, as opposed to a "one-fits-all" approach, are essential. To summarize, the method used to learn individual characteristics (the predicted thermal sensation) is important to generate the information needed for a successful nudge (increasing the number of visitors). This study aims to present a statistical modeling approach to learning individual thermal sensations.

Another critical issue in achieving our goal is that guidelines have not yet been established regarding thermal sensation in outdoor environments, although some detailed standards have been established for indoor environments, such as the ASHRAE Standard 55 [20]. Therefore, many studies have been conducted to understand thermal sensation for various outdoor environments.

A field survey is recognized as the most appropriate methodology for updating current insights into outdoor thermal sensation [21]. Through field surveys, subject responses to thermal sensation (thermal sensation vote, TSV) are usually related to meteorological parameters, and their relationships are often formulated using linear regression [3,6,21–24]. These processes have been reported in many previous studies. However, statistics of TSV, such as thermal neutral temperature, appear to be rather scattered even in comparable climate conditions. Several studies have reported that this variation is expected because of various psychological and behavioral factors, which have a larger influence on thermal sensation in outdoor environments than in indoor environments [4–7,22–27]. In other words, non-measured factors such as each individual's thermal experience, thermal expectation, cultural background, and duration of exposure affect his/her TSV. For example, the change of season from summer to winter causes an upward shift of subjects' neutral temperature [5,7]; people inhabiting hot and humid regions have higher thermal tolerance levels that those inhabiting temperate regions [6,26]. Reduced thermal expectations lead to widely acceptable satisfaction for thermal environments [21]; moreover, thermal sensation is affected by culture, with individuals displaying different TSVs depending on his/her cultural background [27]. The model structure for predicting thermal sensation becomes complicated if individual variations due to various non-measured factors are considered, implying the need to estimate many model parameters. To obtain reliable estimates for many model parameters, in other words, acceptable uncertainty levels in model-predicted thermal sensation, data of sufficient quality and quantity are required. This implies substantial effort over long periods of time (and therefore substantial costs).

To address this problem, previous studies have often simplified the model structure (e.g., simple linear regression) so that estimates can be made with less data. A relevant issue is that this approach involves uncertainty in the estimation of model parameters because regression models are highly sensitive to data availability. However, uncertainties of parameters and the consequent uncertainties of model-predicted thermal sensation have received considerably less attention in the field of outdoor thermal sensation. Furthermore, this approach often focuses